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CC/C-130J Human Vibration Investigation: Synchrophaser Effects

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Interim Report for December 2004 to April 2005

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14. ABSTRACT

The purpose of this investigation was to evaluate the effects of several synchrophaser settings on human vibration transmission in the cabin of the CC-130J and C-130J aircraft. The investigation supported the Air Force Flight Test Center (AFFTC) and the Air Systems Command Global Reach Special Programs Office, C-130 Development System Office (ASC/GRB). The synchrophaser settings included OFF (no synchrophaser), DEF (default synchrophaser setting), OPT 1 (option 1 synchrophaser setting) and OPT 2 (option 2 synchrophaser setting). Triaxial acceleration measurements were made on the troop seat pan and on the floor beneath the seat for the right, center, and left seat locations in the vicinity of the propeller plane, and at seat locations just forward of the troop doors (CC-130J only). Six passengers participated in the study, providing vibration data for a statistical analysis of synchrophaser setting effects. The OPT 2 synchrophaser setting provided the most effective mitigation of the highest seat pan vibration associated with the blade passage frequency, but had little effect in reducing the substantial floor vibration. The effects on human comfort perception were inconclusive.

15. SUBJECT TERMS

human vibration, acceleration, propeller-driven aircraft, synchrophaser

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PREFACE

This report describes the study conducted by the Air Force Research Laboratory, Human Effectiveness Directorate, Biosciences and Protection Division, Biomechanics Branch (AFRL/HEPA), Wright-Patterson AFB, OH, to document and evaluate the effects of selected synchrophaser settings on human vibration aboard the CC-130J and C -130J aircraft. The study was conducted at the request of the Aeronautical Systems Center, Mobility Systems Wing, C-130 Systems Group, Wright-Patterson AFB, OH (MSW/C130SG), and the Air Force Flight Test Center (AFFTC). The POC was Mr. Edward George (418 FLTS/DOEF). The Principal Investigator for the vibration study was Dr. Suzanne D. Smith (AFRL/HEPA). Noise data were also collected by the AFFTC 412 TW and AFFTC 418 FLTS located at Edwards AFB. Major Drew Widing (AFRL/HEPA) coordinated the data collection activity in the cabin area of the aircraft. The AFFTC 412 TW provided a CC-130J aircraft (Tail Number 99-1433) and C-130J aircraft (Tail Number 98-1355). The propellers were balanced on both aircraft. Vibration data were collected during one flight on the C-130J on 7 Dec 2004 and during one flight on the CC-130J on 8 Dec 2005 at Edwards AFB, CA. During each flight, the effects of four synchrophaser settings (including the OFF condition) were evaluated at three altitudes for each aircraft (10K ft MSL, 24K ft MSL for the CC-130J and 31K ft MSL for the C-130J, and 500 ft AGL). The Remote Vibration Environment Recorder (REVER) was used to measure accelerations at the troop seat pan and on the floor beneath the seat for the right side, center, and left side passenger locations in the propeller plane and near the troop doors on the CC-130J. Due to complications with the equipment, data collection was limited to the propeller plane on the C-130J. At 10K and 24K ft MSL/31K ft MSL, six passengers rotated among the six seat locations for each synchrophaser setting. At 500 ft AGL, the passengers remained seated at one location due to buffeting. The investigation focused on the effects of the synchrophaser setting on the vibration associated with the blade passage frequency (100-Hz one-third octave frequency band or 102 Hz constant bandwidth). Human comfort was assessed in accordance with the ISO 2631-1: 1997.

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The authors acknowledge the assistance of Major Drew Widing, AFRL/HEPA, who assisted in equipment setup on the aircraft, and who coordinated all cabin noise and vibration measurements on both the CC-130J and C-130J. Mr. Raymond Newman, Advanced Engineering Information Services, Inc., is also recognized for his assistance in the setup and initial checkout of the REVER systems.

CC/C-130J HUMAN VIBRATION INVESTIGATION: SYNCHROPHASER EFFECTS

INTRODUCTION

Purpose

The purpose of this investigation was to evaluate the effects of several synchrophaser settings on the vibration transmitted to the seated passengers (human vibration) and at the floor in the cabin of the CC-130J (Long) and C-130J (Short) aircraft. The investigation conducted by the Air Force Research Laboratory, Human Effectiveness Directorate, Biosciences and Protection Division, Biomechanics Branch (AFRL/HEPA) supported the Air Force Flight Test Center (AFFTC) and the Aeronautical Systems Center, Mobility Systems Wing, C-130 Systems Group (MSW/C130SG). The synchrophaser settings included OFF (no synchrophaser), DEF (default synchrophaser setting), OPT 1 (option 1 synchrophaser setting) and OPT 2 (option 2 synchrophaser setting). Triaxial acceleration measurements were made at the interface between the seated passenger and the troop seat pan and on the floor beneath the seat for the right, center, and left seat locations in the vicinity of the propeller plane, and at seat locations just forward of the troop doors (CC-130J only). Six passengers participated in the study, providing vibration data for a statistical analysis of synchrophaser setting effects.

Background

In February, 2001, AFRL/HE teamed with the Air Systems Command Global Reach Special Programs Office, C-130 Development System Office (ASC/GRB) (now MSW/C130SG), the Air Force Flight Test Center (AFFTC), the Air Force Reserve Command (AFRC), and the Air Force Institute for Environmental, Safety, and Occupational Health Risk Analysis (AFIERA), to support the WC-130J Human and Equipment Vibration Environment Investigation (amendment to WC-130J QT&E Test Plan, TIS 99066). The investigation was prompted by Deficiency Reports (CAT 1 DR #FB2805000286 and CAT 2 DR #FA9107000029), which described very

uncomfortable and even intolerable vibration generated at various times during flight and centered in the propeller plane where the WC-130J Dropsonde Officer (DSO) and Aerial Reconnaissance Weather Officer (ARWO) stations were located. The study characterized the noise and vibration transmitted to the crewmembers and passengers at selected locations onboard the WC-130J, as well as the C-130J Slick version of the aircraft used to carry troops, for selected aircraft configurations and flight test conditions. The results of the AFRL/HE effort (1) and the Preliminary Report of Results (PRR) (2) showed that dynamically balancing the propellers could significantly reduce the transmission of vibration to the crewmember via the seat pan at the rotor speed of the WC-130J (17 Hz or 16 Hz one-third octave frequency band). The reductions were significant for vibration along the longitudinal and vertical axis of the aircraft. The higher vibration occurring in the lateral plane of the aircraft did show a notable reduction in level. Synchrophasers that adjust the phase angle between engine propeller blades are designed to reduce the noise and vibration associated with the blade passage frequency (102 Hz or 100 Hz one-third octave frequency band in the six-bladed C-130J variants). It was found that the synchrophaser setting on the aircraft was ineffective in reducing the noise and vibration. As part of the C-130J Block Upgrade (BU) 5.4, selected C-130J aircraft variants were modified to include three synchrophaser settings designed to reduce higher frequency vibration. This study characterized the effects of these synchrophaser settings on the vibration transmitted to the seated passengers and at the floor.

METHODS AND MATERIALS

Aircraft Equipment and Test Personnel

The AFFTC 412 TW provided a CC-130J aircraft (Tail Number 99-1433) and C-130J aircraft (Tail Number 98-1355) for this investigation. The propellers were statically balanced at the factory but not dynamically balanced on either aircraft. Flight crew personnel were also provided by the AFFTC 412 TW (test pilots, test conductor, crew chief). The six volunteer passengers were members of the AFFTC 412 TW and 418th Flight Test Squadron (FLTS). One individual from AFRL/HE coordinated both the noise and vibration data collection activity. A

second individual from AFRL/HE acted as the vibration investigator and focused on collecting the vibration data.

Vibration Measurement Equipment and Measurement Locations

The Remote Vibration Environment Recorder (REVER) was used to collect the acceleration data at specified locations. Two REVERs were used to collect the data onboard the CC-130J. Each REVER includes a battery-operated 16-channel data acquisition unit (DAU) measuring approximately 16.5 cm x 10 cm x 4 cm. The DAU enclosure was fabricated using Delrin and T6-6061 aluminum and provided EMI (electromagnetic interference) shielding. Two types of battery packs were available for use depending on the flight time. The first was rated at 12 volts/2.1 amp-hours and measured approximately 5 cm x 9 cm x 3 cm. The battery operated for up to two hours. The second was rated at 12 volts/3.5 amp-hours and measured approximately 7 cm x 9 cm x 3 cm. This battery operated for up to 3.5 hours. Two battery packs were connected to each DAU to extend the operation time. The total system weighed 1.4 kg - 1.6 kg (3.0 – 3.5 lbs) depending on the battery selection. One DAU was located beneath the left troop seats in the vicinity of the propeller plane (CC-130J and C-130J) (Figure 1). The second DAU was located beneath the left side troop seats near the troop door (CC-130J only).

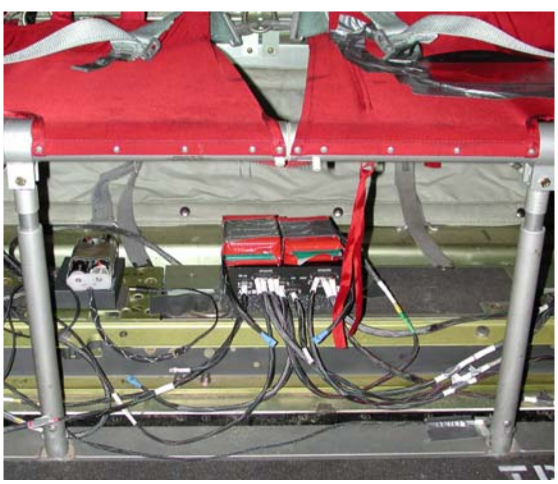

Figure 1. DAU Locations in CC/C-130J Aircraft

Triaxial accelerometer packs and pads were attached to selected sites for measuring accelerations in the fore-and-aft (X), lateral (Y), and vertical (Z) directions as listed in Table 1 Vibration Measurement Locations and Directions and illustrated in Figure 2. The packs were comprised of miniature accelerometers (Entran EGAX-25, Entran Devices, Inc., Fairfield, NJ) arranged orthogonally and embedded in a Delrin® cylinder. Pre- and post-calibrations were conducted on all accelerometers. The comparison method was used with an accelerometer traceable back to the National Institute of Standards and Technology (NIST).

Table 1. Vibration Measurement Locations and Directions

C-130J	PROPELLER PLANE			CC-130J	PROPELLER PLANE		
	RIGHT	CENTER	LEFT		RIGHT	CENTER	LEFT
SEAT PAN X	X	X	X	SEAT PAN X	X	X	X
SEAT PAN Y	X	X	X	SEAT PAN Y	X	X	X
SEAT PAN Z	X	X	X	SEAT PAN Z	X	X	X
FLOOR X		X	X	FLOOR X	X	X	X
FLOOR Y		X	X	FLOOR Y	X	X	X
FLOOR Z		X	X	FLOOR Z	X	X	X
C-130J	TROOP DOORS			CC-130J	TROOP DOORS		
	RIGHT	CENTER	LEFT		RIGHT	CENTER	LEFT
SEAT PAN X				SEAT PAN X	X	X	X
SEAT PAN Y				SEAT PAN Y	X	X	X
SEAT PAN Z				SEAT PAN Z	X	X	X
FLOOR X				FLOOR X	X	X	X
FLOOR Y				FLOOR Y	X	X	X
FLOOR Z				FLOOR Z	X	X	X
Note: Floor directions are relative to occupant seat. Seats are rotated 90 degrees from aircraft longitudinal axis.							

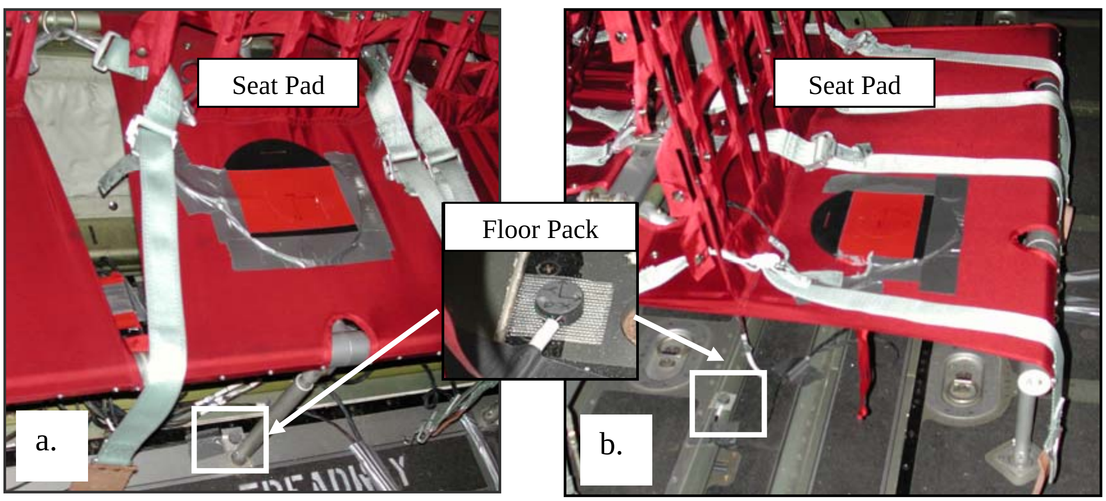

Figure 2. Troop Seat Accelerometer Pad and Pack, a. Side Seat, b. Center Seat

Each accelerometer pack measured 1.9 cm in diameter and 0.86 cm in thickness and weighed approximately 5 gm (25 gm with connecting cable). Triaxial seat pads were used for measuring the vibration transmitted to the passenger via the seat pan in accordance with the International Standards Organization “Mechanical Vibration and Shock – Evaluation of Human Exposure to Whole-Body Vibration – Part I: General Requirements (ISO 2631-1: 1997) (3). The pad consisted of a flat rubber disk approximately 20 cm in diameter and weighing 355 gm (with connecting cable). Embedded in the disk was a triaxial accelerometer pack. Cable

connections between the accelerometers and DAU were made via break-away connectors (when necessary) that required less than 21.8 N (4.9 lbs) to separate. For the CC-130J, the two REVERs were daisy-linked via cable to provide simultaneous data collection at all selected sites. The DAU, battery packs, cables, accelerometers, seat pads, and other auxiliary equipment were secured using heavy-duty mounting tape and/or duct tape. A laptop computer was used to balance all accelerometers and arm the system prior to data collection. A triggering device, measuring 7.6 cm in length and 2.2 cm in diameter with a weight of 20 gm, was used by the AFRL/HE vibration investigator to initiate data collection.

Table 2. Passenger Weight and Height

PASSENGER	WEIGHT (kg/lbs)	HEIGHT (cm/in)	INITIAL LOCATION
A	65.8/145	175.3/69	Left Prop
B	104.3/230	177.8/70	Ctr Prop
C	79.4/175	185.4/73	Right Prop
D	98.0/216	177.8/70	Right Door
E	68.0/150	162.6/64	Ctr Door
F (CC-130J) F (C-130J)	70.3/155 -----------	175.3/69 -----------	Left Door Left Door

Table 2 lists the body weights and heights estimated by the passengers. All acceleration measurements were relative to the human body coordinate system. In the CC/C-130J aircraft, all passengers sat sideways. Fore-and-aft seat pan and floor measurements corresponded to the lateral direction in the aircraft; lateral seat pan and floor measurements corresponded to the fore-and-aft or longitudinal direction in the aircraft.

Data Collection and Processing Methods

Test conditions included three altitudes and four synchrophaser settings. Data were collected at 500 ft AGL (Above Ground Level) and 10K ft MSL (Mean Sea Level) in both aircraft, and at 24K ft MSL in the CC-130J and 31K ft MSL in the C-130J, for all four synchrophaser settings (OFF, DEFAULT, OPT 1, and OPT 2). The propeller phase angles for DEFAULT were 45, 0, 25, and 40 degrees. The phase angles for OPT 1 were 4, 0, 0, and 52 degrees. The phase angles for OPT 2 were 7, 0, 0, and 34 degrees. At the lower altitude (500 ft AGL), the passengers were required to remain seated and secured with a lap belt and shoulder harness, and did not rotate among the seat locations. Table 2 includes the location of each passenger during measurements at 500 ft AGL. For the higher altitude flights at 10K ft MSL, 24K ft MSL, and 31K ft MSL, the passengers were rotated among the troop seats for each synchrophaser setting. For the CC-130J,

this included the three seats located in the propeller plane and the three seats located near the troop door (Table 1). For the C-130J, data were collected at the three seats located in the propeller plane (Table 1). The locations given in Table 2 were the initial starting locations. Once data were collected at the specified altitude, the passengers rotated clockwise to the next location.

At all locations and for all test conditions (12 combinations of altitudes and synchrophaser settings), acceleration data were collected for 20 seconds. Each 20-second time history was defined as a data segment. Three data segments were collected at each location and for each test condition. Each data segment was filtered at 250 Hz (anti-aliasing) and sampled at 1024 samples per second. The resultant acceleration time history was processed in one-third octave frequency bands in accordance with ISO 2631-1: 1997 (3). Constant bandwidth analysis was also done in 0.5 Hz increments using standard signal processing techniques. Data were evaluated at the rotor speed (16-Hz one-third octave band or 17 Hz for constant bandwidth) and blade passage frequency (100-Hz one-third octave band or 102 Hz for constant bandwidth). The overall root-mean-square acceleration level between 1 and 100 Hz, a, in each direction was calculated as:

$$a = \left[\sum_i a_i^2 \right]^{\frac{1}{2}} \qquad 1$$

where a_i is the root-mean-square acceleration level associated with the *ith* frequency component (in 0.5-Hz increments for constant bandwidth analysis, and at the center frequency of the one-third octave frequency band for proportional bandwidth analysis). The overall weighted acceleration between 1 and 100 Hz, a_w, in each direction was calculated as:

$$a_w = \left[\sum_i (w_{ji}^2 a_i^2) \right]^{\frac{1}{2}} \qquad 2$$

where w_{ji} represents the particular frequency weighting depending on the measurement site and direction at the *ith* frequency component (at the center frequency of the one-third octave frequency band) (ISO 2631-1: 1997).

The combined overall acceleration level, $a_{(combined)}$, was calculated from the one-third octave overall acceleration levels as:

$$a_{(combined)} = \sqrt{a_x^2 + a_y^2 + a_z^2} \qquad 3$$

where a_x, a_y, and a_z are the unweighted overall accelerations in the X, Y, and Z directions, respectively.

The combined overall weighted acceleration level, $a_{w(combined)}$, was calculated from the one-third octave overall weight acceleration levels as:

$$a_{w(combined)} = \sqrt{a_{wx}^2 + a_{wy}^2 + a_{wz}^2} \qquad 4$$

Where a_{wx}, a_{wy}, and a_{wz} are the weighted overall accelerations in the X, Y, and Z directions, respectively. This value is also known as the Vibration Total Value (VTV) used for comfort assessment in accordance with ISO 2631-1: 1997. The resultant 16 Hz accelerations, 100 Hz accelerations, overall acceleration levels, and combined overall accelerations for the three data segments collected for each passenger at each location, altitude, and synchrophaser setting were averaged prior to statistical analysis.

RESULTS

Characteristics of CC/C-130J Frequency Response Spectra

All figures referenced in the RESULTS are located in APPENDIX A. Figure A-1 illustrates an example of the one-third octave acceleration frequency spectra and the associated constant bandwidth frequency spectra. The peak associated with the rotor speed (16 or 17 Hz) is more clearly seen in the constant bandwidth data. The peak associated with the blade passage frequency (100 Hz or 102 Hz) is clearly seen in both types of spectra. Since the peaks occur in very narrow bandwidths, the magnitudes of the peaks are similar at the respective frequency, whether given in one-third octave bands or constant bands. Vibration at lower frequencies below 10 Hz was associated with aircraft turbulence or movement of the passenger during data

collection. In both the CC-130J and C-130J there was substantial low frequency buffeting at 500 ft AGL associated with low level flight.

Seat Location and Direction Effects

The following are observations of the effects of seat location and direction based on plots of the data that focus on the acceleration levels observed with the synchrophaser off (OFF). Statistical analyses of these data are not included in this report.

Seat Pan and Floor Vibration at the Blade Passage Frequency (100 Hz)

Figure A-2 illustrates the mean 100-Hz one-third octave seat pan and floor accelerations +/- one standard deviation for the CC-130J at the propeller plane and troop door locations at 24K ft MSL with the synchrophaser in the OFF position. As noted in the figure, the highest seat pan vibration occurred for the right and left side passengers in the X direction of the seat or lateral direction of the aircraft. As shown for the left side passenger, the lowest seat pan vibration tended to occur in the vertical direction. Lower vibration levels tended to occur at the center seat pan in the respective directions as compared to the side seat locations. As shown in Figure A-2, the seat pan vibration at the troop doors was lower as compared to the levels observed in the propeller plane. In contrast to the seat pan results, the highest floor vibration tended to occur in the Z direction, regardless of the location (side or center). Again, the vibration at the troop doors was lower as compared to the levels in the propeller plane. A comparison between seat pan and floor measurements showed that the X-axis accelerations at the seat pan were substantially higher as compared to the X-axis accelerations at the floor for the side passengers. However, the Z-axis accelerations at the seat pan were lower as compared to the Z-axis accelerations at the floor for the side and center locations.

For the CC-130J, the seat location and direction effects at 10K ft MSL and 500 ft ASL were consistent with the observations described at 24K ft MSL at the blade passage frequency (100 Hz). The vibration measured on the C-130J also showed similar seat location and direction effects as compared to the CC-130J at the blade passage frequency (100 Hz).

Seat Pan and Floor Vibration at the Rotor Speed (16 Hz)

Figure A-3 illustrates the mean 16-Hz one-third octave seat pan and floor accelerations +/- one standard deviation for the CC-130J at the propeller plane and troop door locations at 24K ft MSL with the synchrophasers in the OFF position. The figure shows that the highest seat pan vibration at the rotor speed occurred in the X direction for the side and center seat pan locations. The 16-Hz seat pan vibration at the troop doors was lower as compared to the levels observed in the propeller plane. At the floor, the highest vibration occurred in both the X direction (lateral direction of the aircraft) and Z direction. Again, lower levels of vibration were observed at the troop door as compared to the propeller plane. A comparison between the seat pan data and floor data showed that the X-axis vibration was more similar between the two locations at 16 Hz as compared to the data at 100 Hz. The Z-axis accelerations at the seat pan were lower as compared to the Z-axis accelerations at the floor.

For the CC-130J, the seat location and direction effects at 10K ft MSL and 500 ft ASL were consistent with the observations described at 24K ft MSL at the rotor speed (16 Hz). The vibration measured on the C-130J also showed similar seat location and direction effects as compared to the CC-130J at the rotor speed (16 Hz).

Synchrophaser Setting Effects

Troop Seat Pan Vibration

The Repeated Measures Analysis of Variance and Bonferroni Comparison Test showed that significant effects of the synchrophaser setting occurred at both the rotor speed and blade passage frequency ($p<0.05$). The effects were much more dramatic at the blade passage frequency (100 Hz). The synchrophaser setting was expected to have a primary effect on the vibration levels occurring at the blade passage frequency and is the focus of this section. The effects depended on the aircraft, altitude, seat location, and vibration direction. Figures A-4 and A-5 illustrate the mean 100-Hz one-third octave seat pan accelerations +/- one standard deviation in the propeller plane of the CC-130J at 24K MSL and 10K ft MSL, respectively. The mean values were calculated for each seat location, in each direction, for each of the synchrophaser

settings, and for each of the six passengers. Figure A-6 illustrates the mean 100-Hz one-third octave band seat pan accelerations +/- one standard deviation in the propeller plane of the CC-130J at 500 ft AGL. The mean values were calculated from the three sets of data collected on the particular individual occupying that seat since the passengers were required to be restrained during low level flight (i.e., no rotation). Figures A-4, A-5, and A-6 show that, in most cases, the vibration associated with the blade passage frequency was substantially lower at 500 ft AGL as compared to the higher altitudes. The most dramatic effect of the synchrophaser setting occurred at the right and left side troop seat pans where the higher vibration was primarily observed in the X direction of the seat, particularly at the higher altitudes. At these locations, OPT 2 showed a tendency to produce the greatest reduction in the acceleration level. The result was significant for the right seat at 24K MSL and for the left seat at 10K MSL. Otherwise, both OPT 1 and OPT 2 showed a significant reduction in the acceleration levels as compared to OFF and DEFAULT at the side seats in the X direction at the higher altitudes. At the center seat pan, both OPT 2 and OFF produced the lowest acceleration levels in the X direction at 24K ft MSL. The acceleration levels were similar for OPT 1 and OPT 2 for the center seat in the X direction at 10K ft MSL, but only OPT 2 was found to be significantly lower as compared to the OFF and DEFAULT settings. While Figures A-4 and A-5 show that the results in the other directions were variable at the higher altitudes, the vibration levels at all propeller seat locations in all directions observed using OPT 2 were lower as compared to the lowest level achieved with OPT 2 at the left seat in the X direction. The synchrophaser effects at low altitude (500 ft AGL) showed a significant increase in the acceleration level at the left seat in the X-direction using OPT 1 and OPT 2, in contrast to the results observed at higher altitudes. All of the vibration levels associated with OPT 2 at 500 ft AGL were similar to or lower than the vibration level observed for OPT 2 at the left seat in the X direction at 24K ft MSL and 10K ft MSL.

Figures A-7 and A-8 illustrate the mean 100-Hz one-third octave seat pan accelerations +/- one standard deviation in the propeller plane of the C-130J at 31K ft MSL and 10K ft MSL, respectively. Figure A-9 illustrates the mean 100-Hz one-third octave band seat pan accelerations +/- one standard deviation in the propeller plane of the C-130J at 500 ft AGL. The mean values were calculated as were described for the CC-130J. As with the CC-130J, the vibration associated with the blade passage frequency was lower at 500 ft AGL as compared to

the higher altitudes. On the C-130J, the OPT 2 synchrophaser setting did not have the dramatic effect on the seat pan vibration levels as was observed on the CC-130J at the higher altitudes. It is noted that the OPT 2 vibration levels were based on the mean values from two passengers due to the loss of the sensor data. The mean level using OPT 2 was similar to the levels observed with the OFF and DEFAULT settings. Both OPT 1 and OPT 2 showed a significant reduction in the X-axis vibration at the right seat at 10K ft MSL. In contrast, OPT 1 and OPT 2 tended to be higher or equal to the vibration levels associated with the OFF and DEFAULT setting at the left seat in the X direction at all three altitudes. Figure A-8 shows that, at 10K ft MSL in the C-130J, notable variation in the acceleration levels occurred among the passengers at the left seat in the X direction with OPT 2, as reflected in the relatively large standard deviation. These vibration levels were the highest seen at the seat pan when using OPT 2 in both the C-130J and CC-130J.

Figure A-10 illustrates the CC-130J combined overall seat pan acceleration +/- one standard deviation at the three seat locations in the propeller plane at 24K ft MSL, 10K ft MSL, and 500 ft AGL. A comparison between Figure A-10 and Figures A-4, A-5, and A-6 confirms that the combined overall levels show similar trends as observed for the higher X-axis seat pan accelerations at the blade passage frequency. The results were particularly consistent for the vibration occurring at the side seat locations. The combined overall seat pan accelerations in the C-130J also showed similar effects when compared to the X-axis accelerations at the blade passage frequency.

Floor Vibration

Figures A-11 and A-12 illustrate the mean 100-Hz one-third octave floor accelerations +/- one standard deviation in the propeller plane of the CC-130J at 24K ft MSL and in the C-130J at 31K ft MSL, respectively. The most dramatic effect of the synchrophaser setting on the floor accelerations occurred in the Z direction, regardless of the location (sides or center). The lower levels observed on the CC-130J at the right and left sides when using OPT 2 were significant (Fig. A-11). The floor accelerations measured in the C-130J did not show the effects of the synchrophaser setting observed in the CC-130J. Figure A-12 shows relatively higher Z-axis accelerations at the center floor of the C-130J as compared to the CC-130J, with the lowest levels occurring with the DEFAULT setting.   In contrast, DEFAULT showed significantly

higher Z-axis accelerations at the left floor location. Although not statistically analyzed, both aircraft showed lower floor acceleration levels at 10K ft MSL and 500 ft AGL as compared to 24K ft MSL or 31K ft MSL. At the lower altitudes, there appeared to be no dramatic effect of the synchrophaser setting on the floor accelerations, particularly at the center floor where the higher accelerations were observed. OPT 2 did show the lowest Z-axis floor acceleration levels at the right side of the aircraft at 10K ft MSL.

Vibration Exposure Assessment (ISO 2631-1: 1997)

Figure A-13 illustrates the CC-130J combined overall seat pan accelerations (VTVs) +/- one standard deviation weighted in accordance with ISO 2631-1: 1997 and Eqs. 2 and 4 at the three seat locations in the propeller plane at all three altitudes. The graph includes a line at 0.315 ms^{-2} rms. Below this line, the vibration is considered to be “not uncomfortable” in accordance with the ISO 2631-1: 1997. The figure shows that all of the exposures at the higher altitudes should be perceived as being “not uncomfortable.” Although not shown, this same result was shown at the higher altitudes for the C-130J. However, at 500 ft AGL, the mean values for the CC-130J approached the line, while the standard deviation indicated that several individuals should perceive the vibration as being “a little uncomfortable.” For the C-130J, this same trend was observed except with the synchrophaser OFF setting, where the standard deviations at the three locations were below the line (not shown). The higher weighted levels were due to the low frequency buffeting associated with low level flight.

Psychophysical Effects

The frequency weightings given in ISO 2631-1: 1997 imply that frequency components with similar weighted acceleration levels would be equal with regards to human sensitivity. The Repeated Measures Analysis of Variance and Bonferroni Comparison Test were used to statistically compare the unweighted and weighted combined overall accelerations. The significance of the results ($p<0.05$) did depend on the aircraft variant. For the CC-130J, the weighted acceleration levels at the respective locations indicated that the synchrophaser setting would not have the dramatic influence on human perception as suggested by the actual measured

vibration levels, particularly at the higher altitudes (24K ft MSL and 10K ft MSL). For example, the results indicated that the vibration levels occurring with OPT 2 would be perceived as similar to the vibration levels associated with the other synchrophaser settings (Fig. A-13) as opposed to the significant reductions observed in the actual levels (Fig. A-10), depending on the seat location and altitude. In contrast, for the C-130J at the higher altitudes, the results did indicate that the reductions occurring in the unweighted vibration levels would be perceived by the passengers, particularly at the right seat location in the X direction (note trends in Figs. A-7, A-8, and A-9). In addition, as observed for the comfort assessment, Figure A-13 indicates that the vibration at 500 ft AGL would be perceived as being greater than the vibration occurring at higher altitudes, in contrast to the actual unweighted measurements. The significance of these findings is given in the DISCUSSION.

Subjective Assessments

Formal subjective assessments of the vibration and the effects of the synchrophaser settings were not conducted as part of this study due to the limited time each passenger spent at a particular seat location and the inexperience of many of the passengers with flying on board the CC/C-130J. The limited time was necessary to complete all of the data collection at all four synchrophaser settings for the three altitudes. The passengers were informally queried as to their perception of the synchrophaser effects following the flights. The inexperienced passengers tended to indicate that they did not really notice any change in the vibration with synchrophaser setting, but that the vibration at the seats located near the troop doors was lower than it was in the propeller plane. A few passengers claimed that they felt the vibration more at the right side seat in the propeller plane, although this was not necessarily supported by the measured accelerations. One experienced passenger noted that OPT 1 felt better at 10K ft MSL and OPT 2 felt better at 24K ft MSL in the CC-130J. Figure A-10 does show that OPT 1 and OPT 2 both produced lower vibration levels at the right seat at 10K ft MSL, while OPT 2 produced the lowest vibration at the right seat at 24K ft MSL.

Passengers did comment that the seats became loosened during the flights, causing some individuals to hit the support bar located beneath the seat pan. The cloth seats were periodically

tightened to try and avoid contact with this bar. One passenger in particular commented that having someone sitting next to him affected his perception of the vibration, although it was not clear whether the vibration felt reduced or increased. For connected troop seats, it was expected that the cloth seat pan would become more taut once the adjacent seat was occupied. This could prevent an individual from hitting the support bar.

DISCUSSION

This investigation characterized and assessed the effects of synchrophaser setting on human vibration in the CC/C-130J aircraft. In addition to measuring triaxial accelerations at the seat pan, measurements were also taken on the floor located below the seat. Data were collected at three altitudes for each aircraft. Six passengers were rotated among the seat locations at the higher altitudes to accommodate a statistical analysis of synchrophaser effect.

Although this study emphasized the vibration entering the passenger at the seat pan, the differences in the distribution of the vibration at the seat pan and floor warrant some discussion. These differences were highly dependent on the seat location and vibration direction. Although Figure A-2 illustrates the mean seat pan and floor vibration at 100 Hz for the CC-130J, Figure A-14 emphasizes the relative differences between the two measurements at the center and side passenger locations in the C-130J via stacked plots. The higher floor vibration observed at the center seat location in the Z direction and the higher seat pan vibration observed at the side seat in the horizontal directions were consistent with the trends observed in the previous investigation (Smith, 2002). The floor measurements confirmed passenger judgment that the vibration felt through the feet at the centerline of the aircraft was very high as compared to locations off the centerline towards the sides of the aircraft. However, caution must be taken that this judgment is not extrapolated to the seats, i.e., the highest vibration at the seat occurs at the side locations in the horizontal plane and was most likely influenced by their mounting to the fuselage. Here, the horizontal floor vibration is relatively small compared to the seat. Although the extent to which vibration entered the feet in the seated passenger was unknown, one should not draw the conclusion that the center seats would be more comfortable simply because the seat pan vibration was lower without considering the contribution of the floor vibration at the feet. In addition, the

vibration entering the seat back is also important when assessing the vibration. The webbing that forms the troop seat back rendered this measurement difficult.

The synchrophaser setting did have a significant effect on both the seat pan and floor vibration but was complicated by the dependence on the aircraft, measurement location, and measurement direction. In general, the results strongly suggested that the OPT 2 synchrophaser setting would provide the most effective mitigation of the highest seat pan vibration associated with the blade passage frequency occurring at the side seat locations in the fore-and-aft (X) direction of the passenger or along the lateral axis of the aircraft. Unfortunately, OPT 2 did not appear to be effective in reducing the high vertical floor vibration along the centerline of either aircraft.

The ISO 2631-1: 1997 limits the assessment of vibration exposure to 80 Hz, which excludes the substantial vibration on board the six-bladed C-130J variants in the 100-Hz one-third octave frequency band (or 102 Hz in constant bandwidth). This study included the 100-Hz frequency band in the assessments. The weighted acceleration levels or VTVs shown in Figure A-13 indicated that the vibration, regardless of the length of exposure, should not be uncomfortable at the higher altitudes, yet, historically, subjective comments have indicated that this may not be the case for prolonged flights. This raises an issue with regards to the effects of higher frequency vibration and its direction during prolonged operation of military propeller aircraft. A particular concern is that the significant reduction in the relatively high fore-and-aft (X) seat pan vibration observed in the unweighted data at the blade passage frequency with OPT 2 has little effective contribution to the fore-and-aft (X) vibration weighted over the frequency band from 1 to 100 Hz. The relatively higher weighted accelerations observed at low altitude (500 ft AGL) were due to the contribution of lower frequency vibration associated with buffeting. These lower frequency components are not as highly weighted as the higher frequency components.

CONCLUSIONS

1. The effects of the synchrophaser settings were complex and depend on the aircraft, altitude, location, and direction of the vibration.

2. The OPT 2 synchrophaser setting provided the most effective mitigation of the highest seat pan vibration associated with the blade passage frequency, but had little effect in reducing the substantial floor vibration.

3. The effects of synchrophaser setting on the human perception of comfort were inconclusive. All exposures at the higher altitudes (10K, 24K and 31K ft MSL) were considered "not uncomfortable" according to ISO 2631-1: 1997. The synchrophaser settings did not show the dramatic effect on human perception (using the weighted acceleration levels) as suggested by the actual measured values.

4. Vibration at the troop doors was substantially lower than the vibration occurring in the propeller plane. The vibration levels at this location were considered acceptable.

5. Vibration at the side troop seats could be further reduced by considering alternative methods for attaching the seating system to the aircraft to avoid the transmission of horizontal vibration from the fuselage.

6. The ISO 2631-1: 1997 weighting or sensitivity curves should be evaluated for their applicability to military propeller aircraft environments.

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2. George, Edward J. C-130J Human and Equipment Vibration Environment Investigation. *AFFTC-PRR-01-01*. Air Force Flight Test Center, Edwards AFB CA, March, 2001.

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APPENDIX A

FIGURES

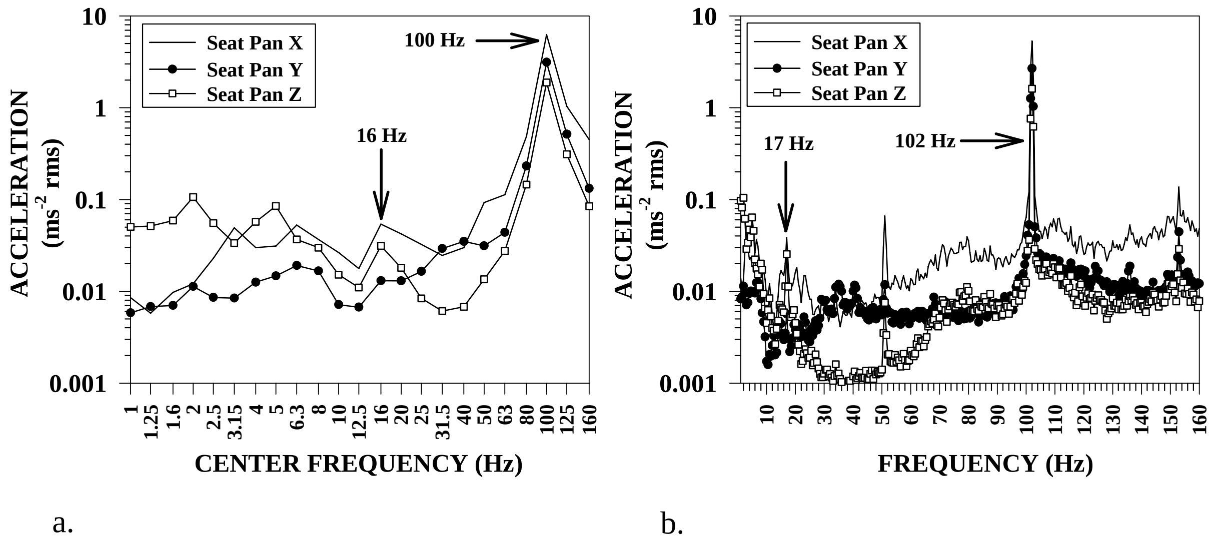

Figure A-1. Example Seat Pan Rms Acceleration Frequency Spectra (CC-130J, Propeller Plane, Left Troop Seat, Synchrophaser OFF), a. One-Third Octave Frequency Spectra, b. Constant Bandwidth Frequency Spectra (0.5 Hz)

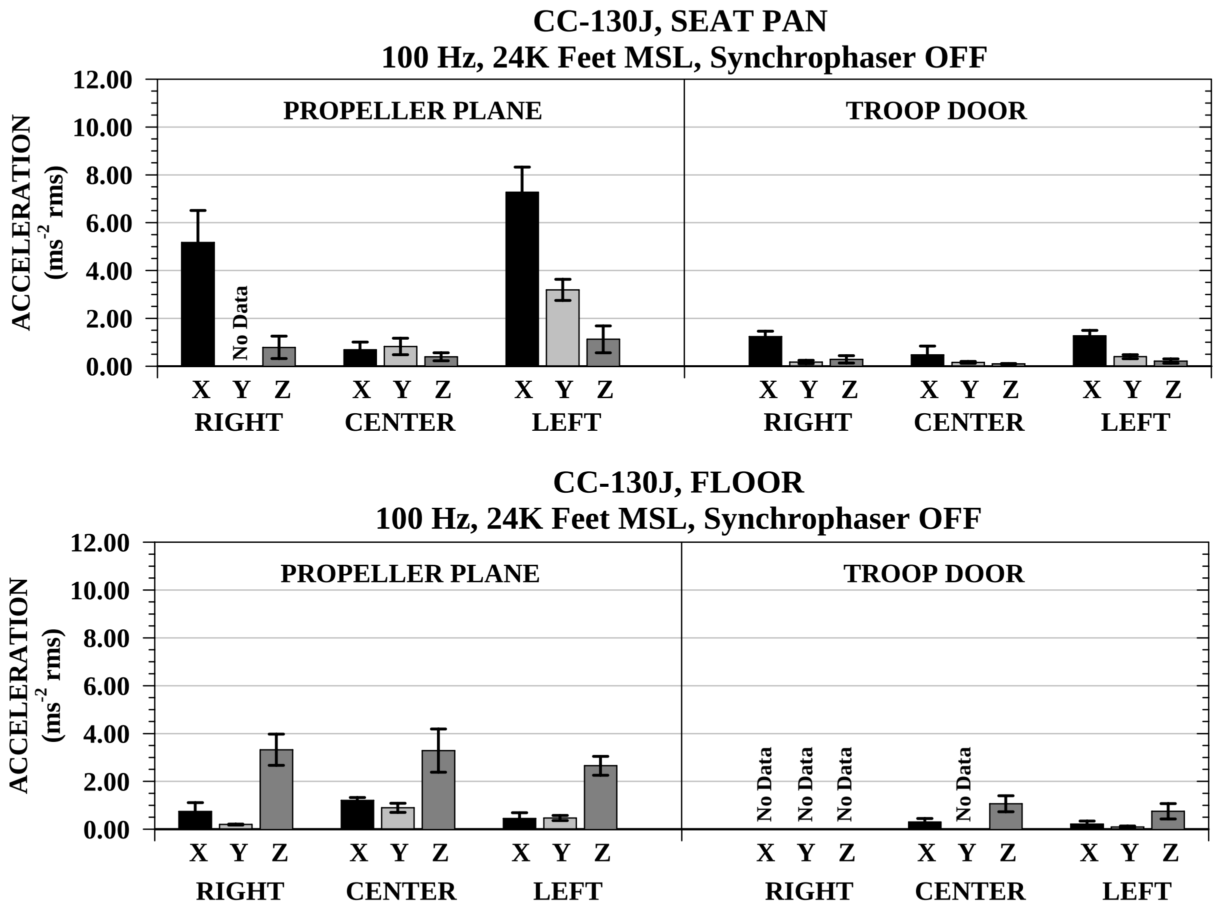

Figure A-2. Mean CC-130J 100-Hz One-Third Octave Seat Pan and Floor Accelerations +/- One Standard Deviation at 24K Feet MSL with Synchrophaser OFF

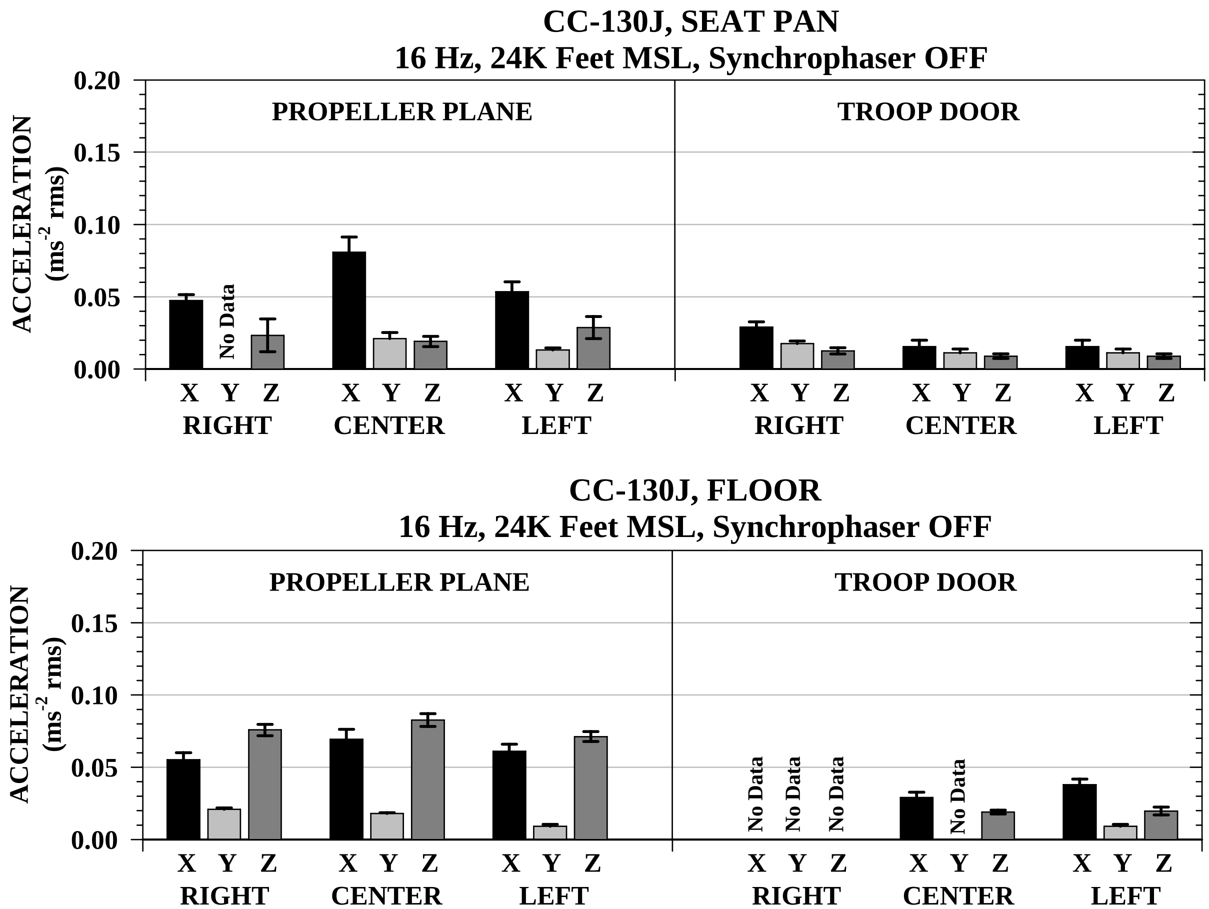

Figure A-3. Mean CC-130J 16-Hz One-Third Octave Seat Pan and Floor Accelerations +/- One Standard Deviation at 24K Feet MSL with Synchrophaser OFF

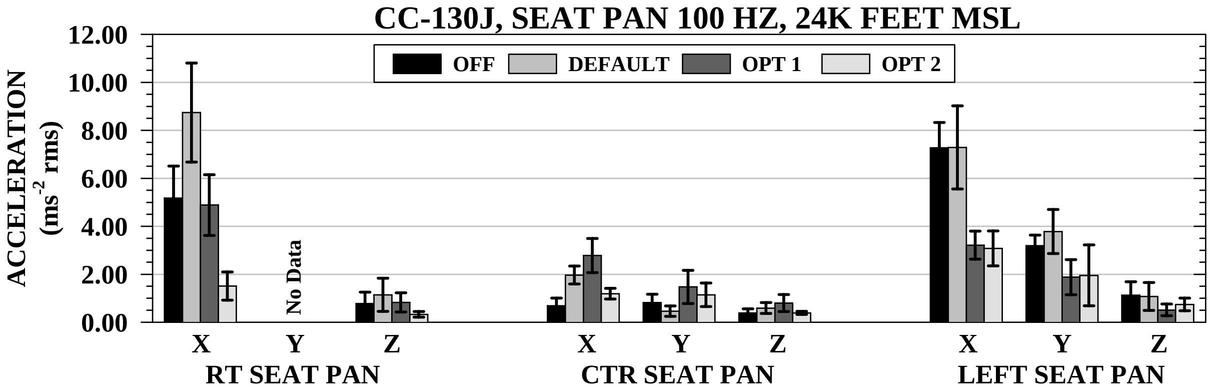

Figure A-4. Mean CC-130J 100-Hz One-Third Octave Propeller Plane Seat Pan Accelerations +/- One Standard Deviation at 24K Feet MSL

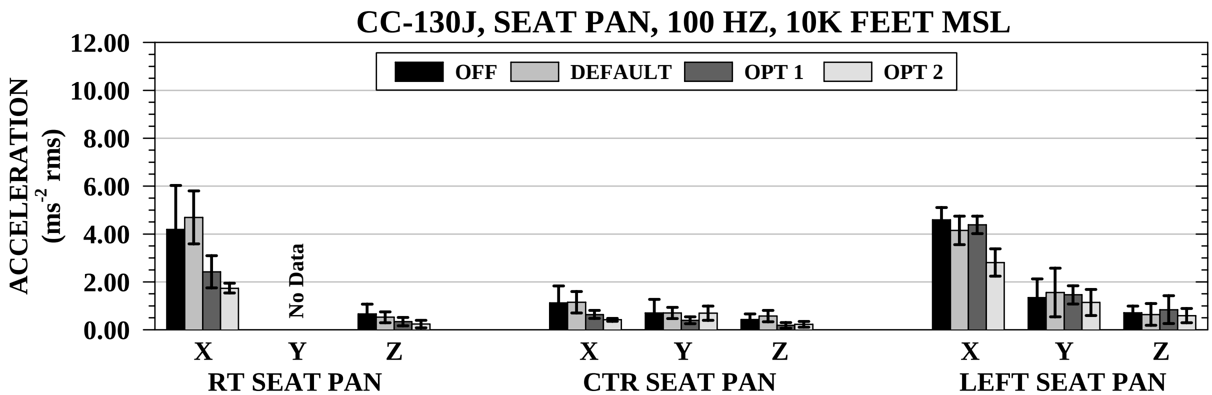

Figure A-5. Mean CC-130J 100-Hz One-Third Octave Propeller Plane Seat Pan Accelerations +/- One Standard Deviation at 10K Feet MSL

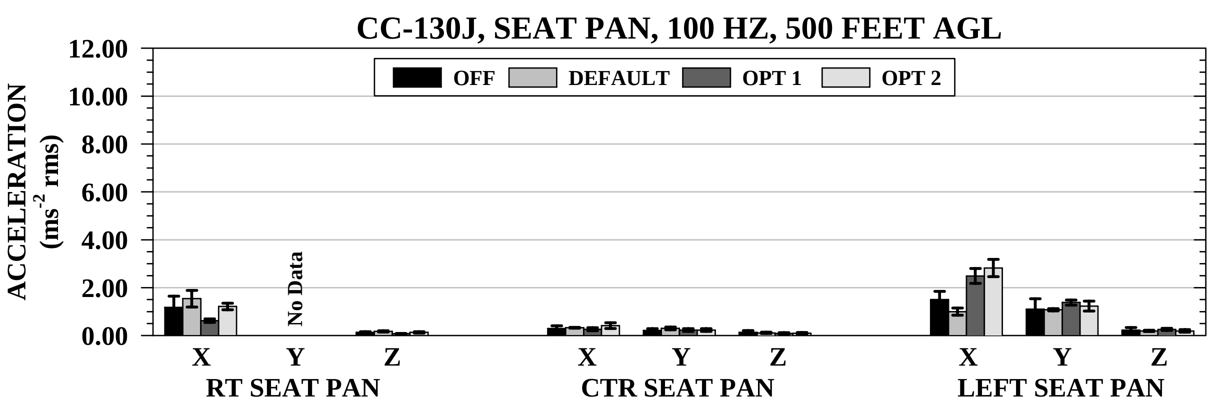

Figure A-6. Mean CC-130J 100-Hz One-Third Octave Propeller Plane Seat Pan Accelerations +/- One Standard Deviation at 500 Feet AGL

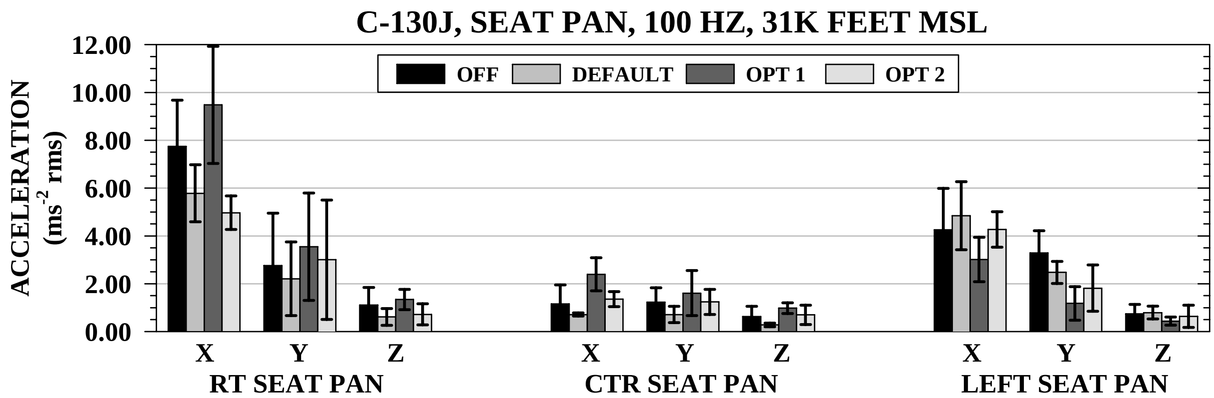

Figure A-7. Mean C-130J 100-Hz One-Third Octave Propeller Plane Seat Pan Accelerations +/- One Standard Deviation at 31K Feet MSL

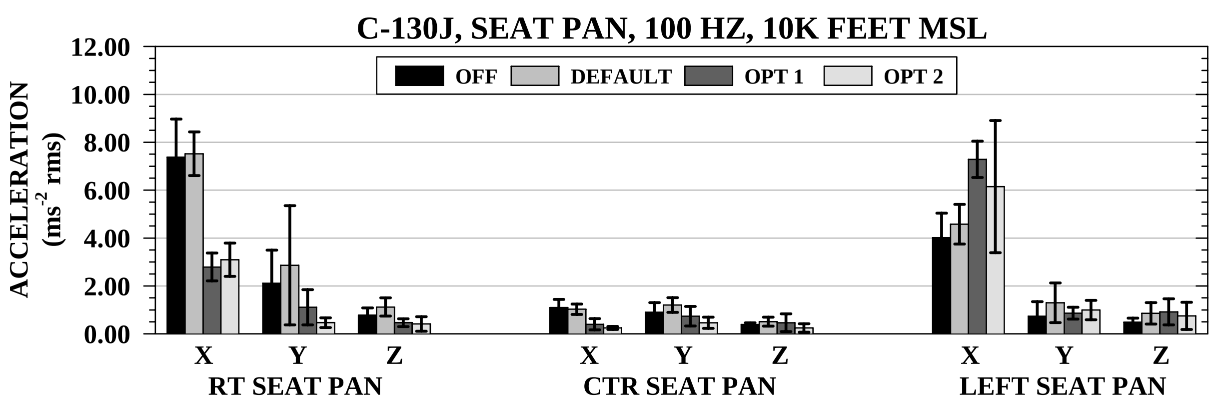

Figure A-8. Mean C-130J 100-Hz One-Third Octave Propeller Plane Seat Pan Accelerations +/- One Standard Deviation at 10K Feet MSL

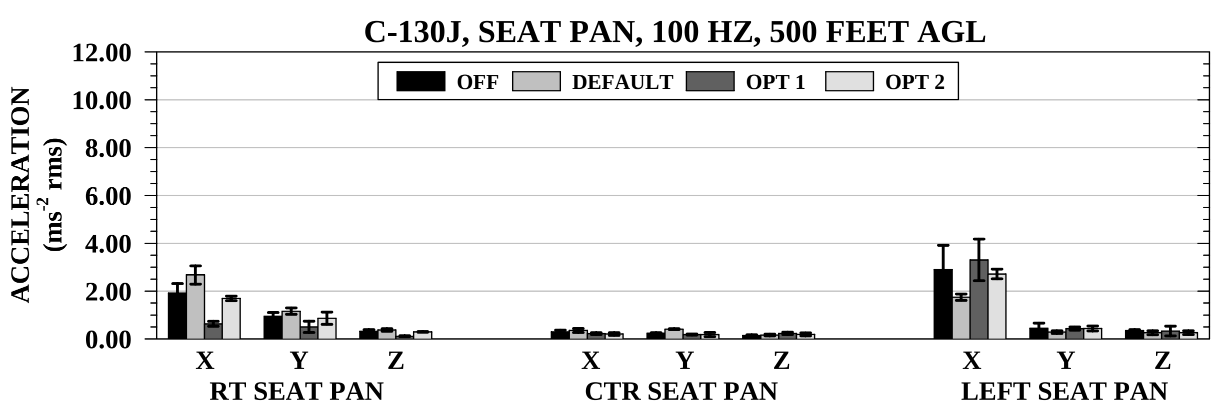

Figure A-9. Mean C-130J 100-Hz One-Third Octave Propeller Plane Seat Pan Accelerations +/- One Standard Deviation at 500 Feet AGL

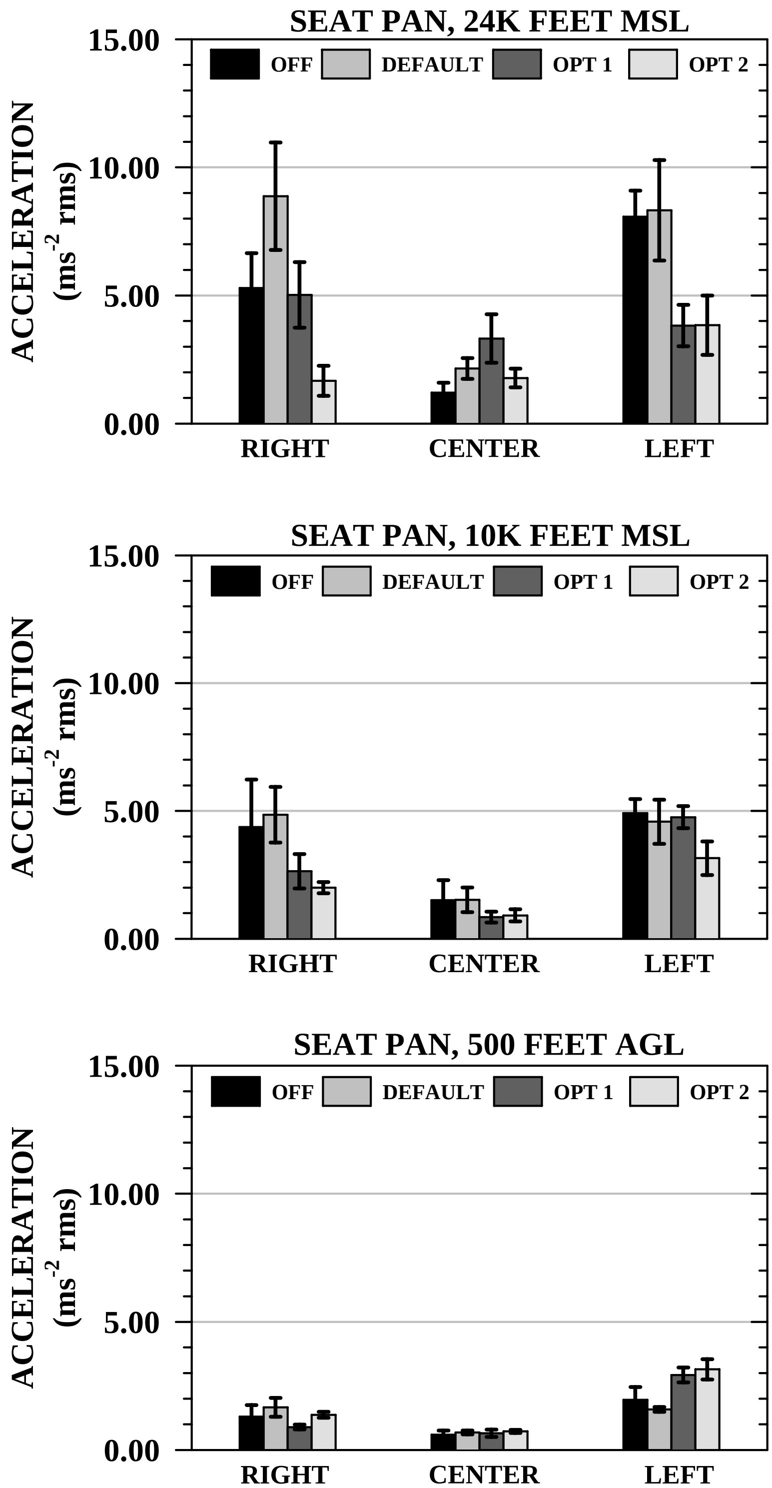

Figure A-10. Mean CC-130J Combined Overall Propeller Plane Seat Pan Accelerations +/- One Standard Deviation (Note: no Y-axis data at right seat pan)

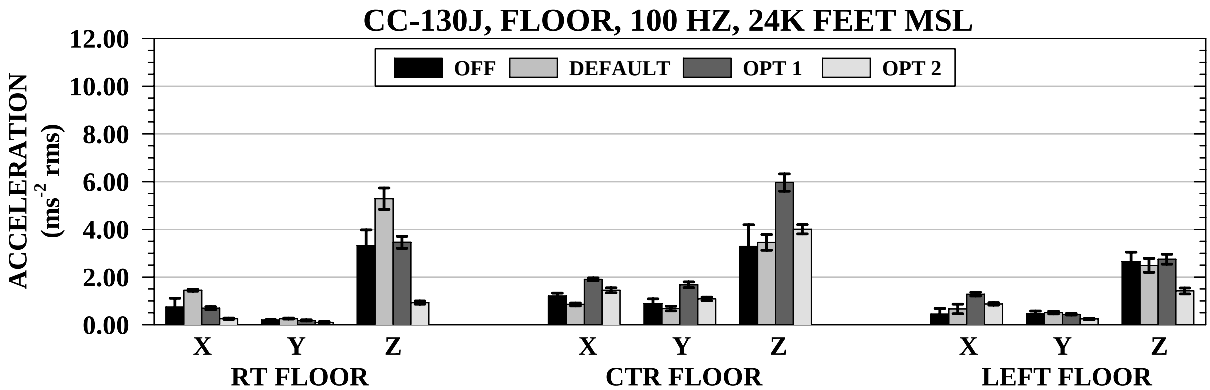

Figure A-11. Mean CC-130J 100-Hz One-Third Octave Propeller Plane Floor Accelerations +/- One Standard Deviation at 24K Feet MSL.

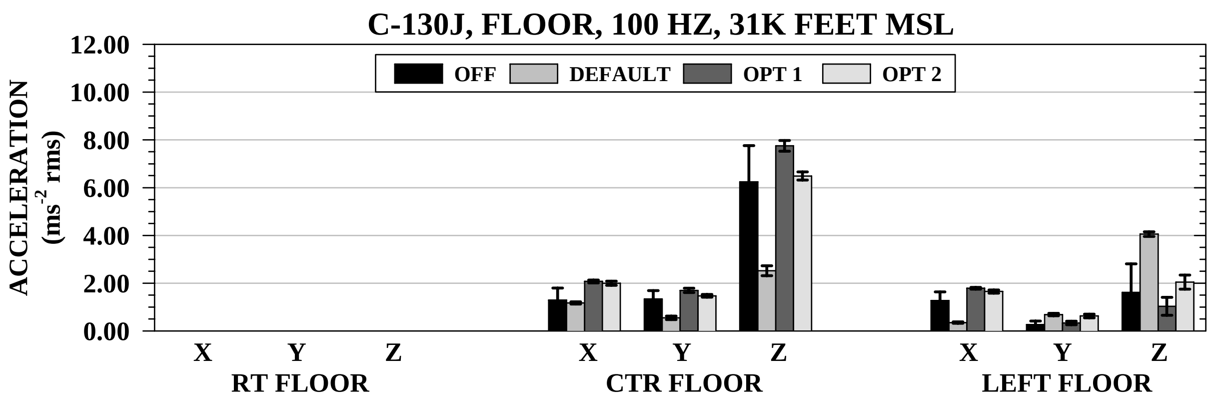

Figure A-12. Mean C-130J 100-Hz One-Third Octave Propeller Plane Floor Accelerations +/- One Standard Deviation at 31K Feet MSL.

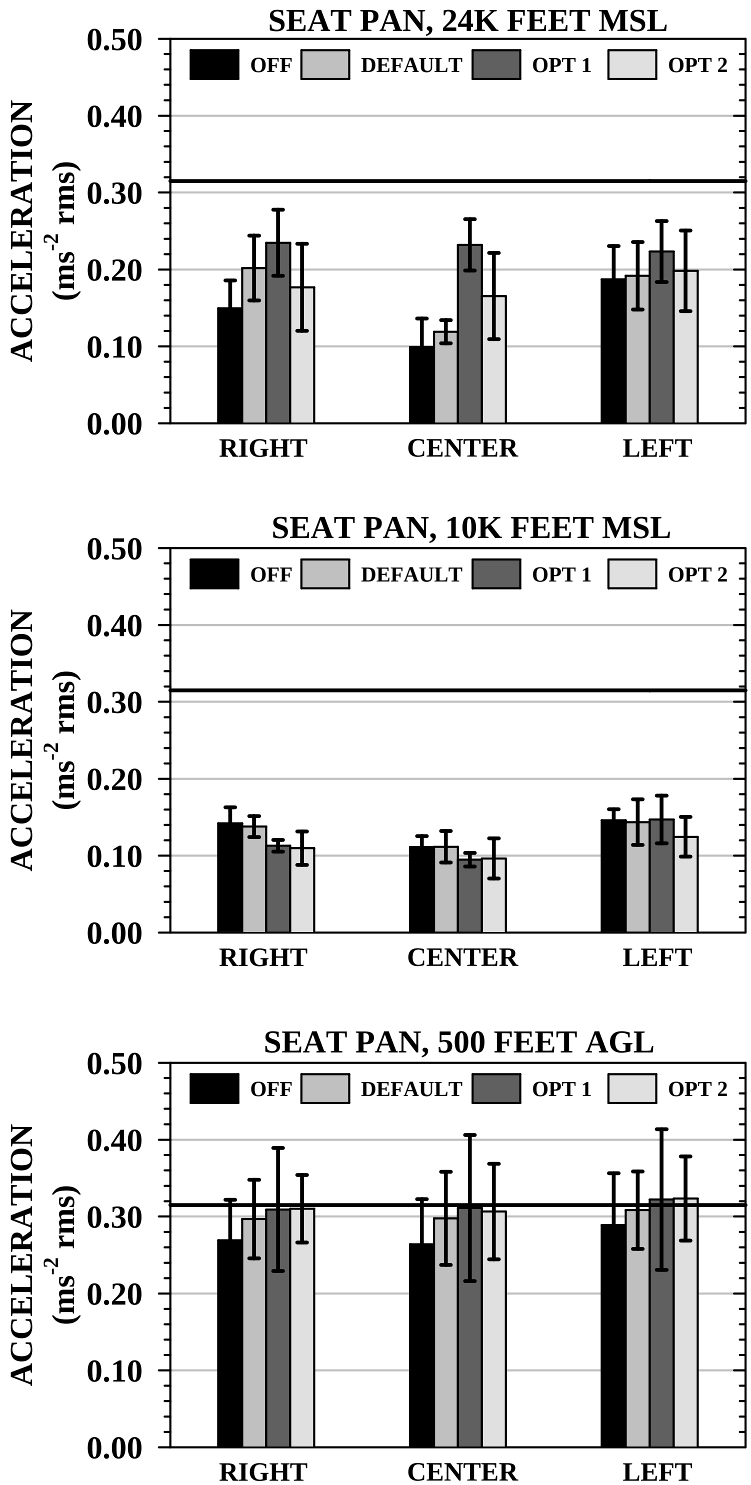

Figure A-13. Mean Weighted CC-130J Combined Overall Propeller Plane Seat Pan Accelerations (VTVs) +/- One Standard Deviation (Note: no Y-axis data at right seat pan)

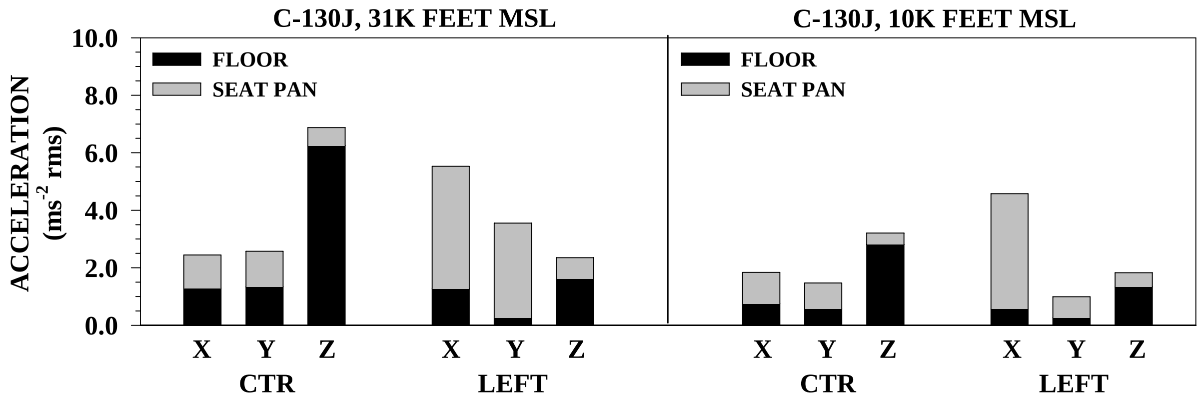

Figure A-14. Mean C-130J 100-Hz One-Third Octave Seat Pan and Floor Accelerations +/- One Standard Deviation.

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17 April 12

MEMORANDUM FOR DTIC-OQ
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SUBJECT: Request to Change the Distribution Statement on a Technical Report

This memo documents the requirement for DTIC to change the distribution statement on the following technical report from distribution statement B to A. Approved for Public Release; distribution is unlimited.

AD Number: ADB315705
Publication number: AFRL-HE-WP-TR-2005-0107
Title: CC/C-130J Human Vibration Investigation: Synchrophaser Effects

Reason for request: The information and representative data contained in this document are valuable resources for government, industrial, and academic institutions involved in the upgrade of subject equipment/aircraft, improvement of human interfaces (such as seating systems and helmet systems) to mitigate deleterious effects of equipment vibration on health and performance, equipment simulator development/enhancement, modeling of human response to equipment vibration, and the development/improvement of equipment design and exposure standards.

Donald Denio

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